

Dance Biomechanics

A Tool for Controlling Health, Fitness, and Training

Yiannis Koutedakis, Ph.D., Emmanuel O. Owolabi, Ph.D., and Margo Apostolos, Ph.D.

Proofs to: y.koutedakis@uth.gr

Abstract

The need for superior performance in dance has impelled teachers and choreographers to use increasingly effective and sophisticated methods of preparation. To that end, such modalities of biomechanics as advanced motion-capture, muscle-function and muscle-strength techniques are being used to provide useful information about which of the dancers' needs require special attention. This often involves improving aspects of dance technique, which, in turn, may help dancers to prevent disabling injuries, the most frequent cause of notoriously short dance careers. Biomechanics may also help dancers to assess fitness levels, to control overtraining or "burnout," and assist them and their teachers in the effective scheduling of practice and exercise sessions.

From the biological sciences point of view, physical performance is mainly a function of an individual's size, shape, sex, age, and physical fitness. In particular, professional dance performance is a complex phenomenon, depending on a large number of interrelated elements that are derived from such dissimilar and

diverse areas as material science, body science, and even space science.¹ These include a number of technical and medical elements, directly related to the discipline of biomechanics, that are used to detect areas of weakness that require special attention.

Biomechanics is the study of the human body in motion. By applying principles from mechanics and engineering, biomechanists are able to study the forces that act upon the body and the effects they produce. In other words, biomechanics is the scientific discipline that studies the mechanical codes of human movement, such as muscle fiber recruitment, by using state-of-the-art technologies and techniques.

Although Aristotle (384-322 BCE) was the first to examine and write about complex movements of the human body, such as running and walking, and Archimedes (287-212 BCE) was the first to examine floating bodies and their movements in water, biomechanics was primarily developed during the 1970s, when there was a widespread tendency for sport coaches

to slavishly copy the training methods and, particularly, the techniques of current champions and present them as models to young hopefuls. More recently it has been established that every individual is biomechanically different and what we perceive as superior technique is uniquely reserved for a specific individual. Nevertheless, biomechanics can help dance educators to detect the root causes of faults (e.g., anatomical imbalances) that arise during particular movements, secure the best possible use of their dancers' natural abilities (talent), and avoid movements that may cause injuries.

Common Biomechanical Techniques

Biomechanists are using a large range of equipment to measure and record time, motion, and force, thereby advancing knowledge in such areas as developmental biomechanics, biomechanics of exercise and sports (including dance), and rehabilitative biomechanics. The most common techniques used worldwide include motion capture, electromyography, dynamography, and dynamometry.

Motion Capture

Over the centuries the evolution of methods for capturing human movement has been motivated by the need for new information on the characteristics of normal and pathological human movement. The optical devices used in biomechanics for this purpose

Yiannis Koutedakis, Ph.D., is from the Department of Sport and Exercise Sciences, Thessaly University, 42100 Trikala, Greece; and the School of Sport, Performing Arts and Leisure, Wolverhampton University, United Kingdom. Emmanuel O. Owolabi, Ph.D., is from the Department of Physical Education, Health and Recreation, University of Botswana, Gaborone, Botswana. Margo Apostolos, Ph.D., is from the School of Theatre, University of Southern California, Los Angeles, California, USA.

Correspondence: Yiannis Koutedakis, Ph.D., Sport & Exercise Sciences, Thessaly University, 42100 Trikala, Greece; y.koutedakis@uth.gr.

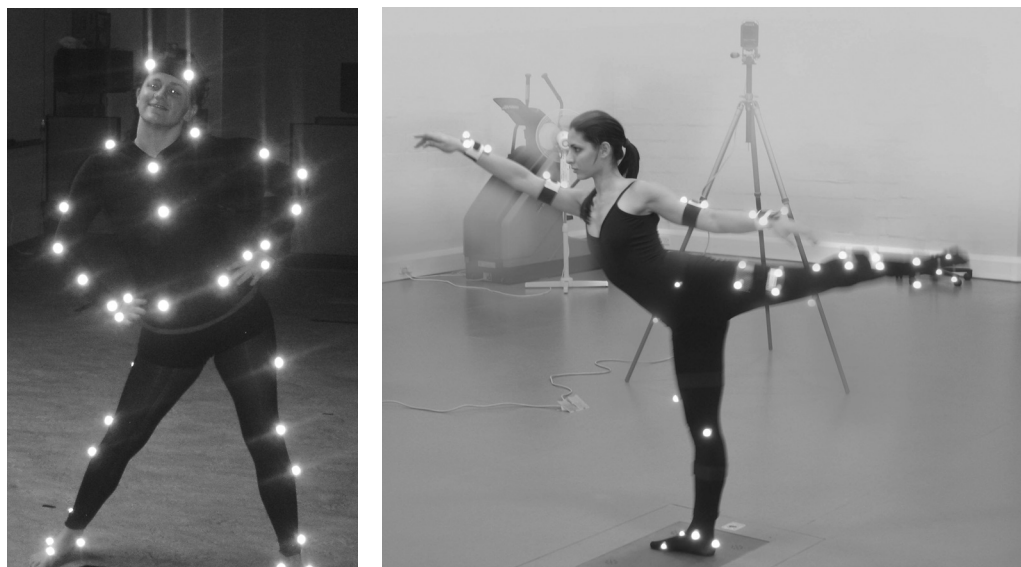


Figure 1 Motion capture is achieved by using infrared illumination of reflective markers placed on the subject to identify bony landmarks and segment locations.

include photography, cinematography, videography, and magnetic resonance imaging. These modalities all generate kinematic data from which kinetic data can be calculated.

Most common methods for accurate capture of three-dimensional human movement require a laboratory environment and the attachment of markers or fixtures to the body's segments. Real time three-dimensional motion capture is achieved by using infrared illumination of reflective markers placed on the subject to identify bony landmarks and segment locations. Cameras record the Cartesian x,y and z coordinates of each marker. Specifically, infrared illumination of the markers allows automatic digitization of two-dimensional marker locations in each camera view. With accurate calibration of camera positions, the two-dimensional coordinate data can be combined to reconstruct the three-dimensional location of the markers. A quick processing of data allows the information to be applied to another set of points, for example those placed on a virtual three-dimensional model. A set of about 30 markers and anywhere from three to 12 infrared high-speed cameras performing at more than 400 frames per second can be used in these procedures. The advancement of markerless approaches has also been considered in view of a more accurate capture of three-dimensional human movement for biomechanical applica-

tions.² The implementation of this new methodology offers the promise of simple, time-efficient, and potentially more meaningful assessments of human movement in research and clinical practice.

Motion-capture techniques (Fig. 1) have recently been used to study the relationship between human body symmetry and dance ability. The association between these two variables was found to be stronger in males than in females.³ Three-dimensional motion capture systems may be employed to assist dancers and their teachers in identifying aspects of technique that require special attention. Furthermore, improvements in dancers' technique through better muscle coordination are normally associated with reduction of injury rates.¹ These tools may also be used to compare dancers with other athletic populations,⁴ produce animations from dance, and extract the important features of a particular gesture. Based on the parameters chosen from subsequent analyses, various mapping between gesture and, say, music may be applied. However, it should be stressed that although motion capture offers alternative points of view in movement analysis, it should be seen as a new medium and not as a replacement for the traditional media and methods.

Electromyography

Electromyography (EMG) provides data on muscle activity. Consisting

of a receiver, electrodes, and a data acquisition system, an electromyograph records electrical changes that occur in a muscle during or just prior to contraction. This electrical activity can be captured, amplified, filtered, and recorded as an indication of muscle activity during a performance.

Surface EMG of major muscle groups has been used to study movement characteristics in both dancers⁵ and non-dancers,⁶ often in synchrony with motion capture techniques and force platforms.⁷ For instance, the balance of trained ballet dancers and non-dancer controls was mechanically perturbed in order to evaluate the time of onset and the consistency of muscle activation.⁸ Results supported the prediction that ballet dancers have significantly faster neuromuscular responses than controls, and are significantly more consistent in muscle activation. These findings indicate a superior postural control mechanism in trained dancers and may explain the ability of dancers to maintain static balances over a small base of support. It has also been found that initiating gait from toe-standing permits the generation of great amounts of forward momentum, which may be advantageous for dancers and athletes in certain situations.⁷ Electromyographic analyses of grand-plié in ballet and modern dancers revealed differences between these two forms of dance,⁵ while principals in a ballet company

were found to demonstrate lower EMG at rest than soloists or corps de ballet dancers.⁹ EMG techniques have even been used to gain insight into the coordinative structure of complex dance movements,¹⁰ and to analyze the neuromuscular independence of the abdominal wall muscles in trained dancers.¹¹

Dynamography

A dynamograph records forces produced during an activity. One such device is the force platform, which is basically an electromechanical apparatus that generates electrical signals proportional to the components of force acting on it. The most common use of force platforms is to measure the reaction forces between the foot and the floor during locomotor activities such as walking, running, and dancing. Mounted on the ground¹² or on different kinds of exercise equipment,¹³ force platforms incorporate into their structure a number of force transducers that can be either strain gauges capable of altering their electrical resistance with strain, or piezoelectric elements that generate charge when stressed. The electrical energy produced can then be used to assess the forces generated during contact with the device during a variety of activities.

By using a force platform with high frequency motion capture facilities it has been revealed that dancers' jumping strategies are more related to individual characteristics than to training background.¹² In an attempt to expand the knowledge of the magnitude and rate of applying axial forces during actual dance in relation to the etiology of chronic injuries and osteoarthritis, Simpson and Kanter¹⁴ found that high impact situations create significant force levels (e.g., up to 14 times the dancers' body weight) that could contribute to the excessive joint wear often observed in these individuals.

Dynamometry

Dynamometry involves the use of strain gauges, mechanical¹ and computer-assisted hand-held¹⁵ dynamom-

eters, as well as computerized equipment with accommodating speed and resistance facilities (also known as isokinetic dynamometers, Fig. 2). The latter are machines designed to measure muscle torque and body (or limb) segment rotational speed, from which power production can be calculated. They can incorporate an isokinetic resistance mode (where testing and rehabilitation is totally accommodating throughout the entire range of motion, and resistance continuously matches muscular efforts), a reactive eccentric mode (where machines respond only to the examinee's force outputs; to initiate movement the dancer, athlete, or patient must produce and maintain a pre-determined minimum amount of force), a passive motion mode (which allows patients to work safely at prescribed sub-maximal force levels while combining isometric, concentric, and eccentric contractions), an isotonic mode (which allow velocity to vary during the application of inertia-free constant forces), and an isometric mode (commonly used when pain associated with motion is a factor).

There are unfortunately no universally agreed upon isokinetic machine testing procedures for muscle function, mainly because in many laboratories the tests used are dictated by the design of the isokinetic dynamometer. Nevertheless, isokinetic exercise and assessment not only presents a scientific basis for the use of isokinetics, it also provides practical guidelines for applying isokinetics in clinical practice, particularly in the management of chronic injury.¹⁶ Repeated contractions using such equipment may provide an insight into the fatigability of muscle groups and how specific training alters this particular aspect of muscle function. For instance, with increased velocity a decreased or incomplete activation of fast twitch muscle fibres may occur during bilateral actions compared to unilateral equivalents.¹⁷ Thus it has been shown that dancers demonstrate higher eccentric knee extensors endurance,¹⁸ and command different muscle strength characteristics,¹⁹ com-

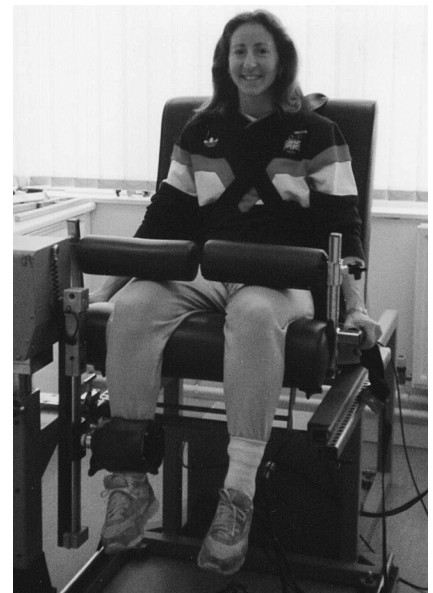


Figure 2 Leg strength assessment on an isokinetic machine.

pared to non-dancers. In conjunction with exercise magnetic resonance spectroscopy (MRS), isokinetic dynamometers provide a non-invasive and simultaneous quantification of muscle energy state over time at rest and during exercise.²⁰

Injury Prevention

According to the World Health Organization, health is defined as a state of complete physical, mental, and social well-being. This definition goes beyond the traditional view of health, which for thousands of years was perceived as merely the absence of disease or infirmity. However, placing illness (or injury) on one side of a line and health on the other is still a common practice. Most dancers, for instance, see health simply as the absence of any serious skeletal, joint, or muscle injuries that prevent them from fulfilling their artistic aspirations. In response to this traditional point of view, most of the available literature in dance medicine and science has dealt with injuries and their treatment. The result has been the creation of a treatment-oriented culture that pays little attention to injury prevention and the elimination of health risks, such as overtraining (or "burnout"). Nevertheless, musculoskeletal screening, for instance, seems to be invaluable

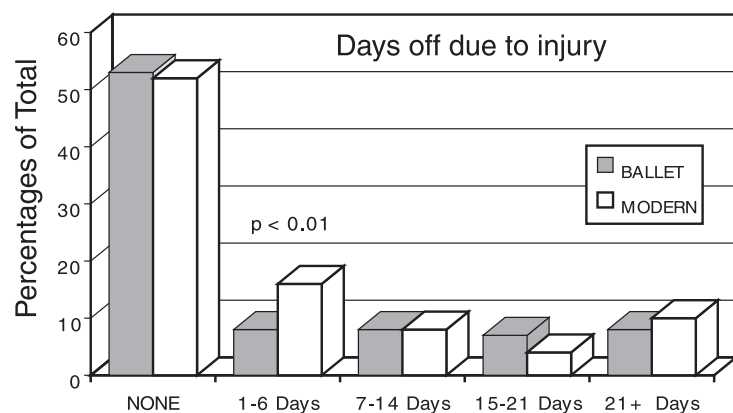


Figure 3 Days off due to injury in professional ballet and modern dancers [data is from Koutedakis and colleagues²² and is expressed in percent of the total (n = 324) sample].

for revealing deficits in muscle and joint flexibility and in muscular stability and control, and while the link between correcting these deficits and improved performance can be hard to prove, the growth in popularity of musculoskeletal screening among professionals in the field over the last few decades lends a heavy weight of anecdotal and clinical evidence to support its efficacy.

Over the last half century the study of the body's mechanical response to various environmental conditions, particularly to impact, has led to numerous advances with biomechanical relevance. This includes the formulation of injury metrics, injury classifications and risk probabilities, the mechanical characterization of biological systems, and the understanding of injury and mechanisms of trauma. Research using such techniques revealed that professional dancers have a 90% risk of injury during their career,²¹ while injury is perhaps the single most frequent cause of time lost from dance. In a period of 12 months almost 50% of a large sample of professional dancers reported one to six days off due to a musculoskeletal injury (Fig. 3). The lower back seems to be the most frequently injured site, which together with pelvis, legs, knees, and feet accounts for more than 90% of the injuries.²² Both external (e.g., type of movement) and internal (e.g., anatomical abnormality) factors have been implicated in the develop-

ment of such injuries. Poor posture increases the stress on supporting structures (e.g., bones and ligaments) and therefore the risk of developing an injury. Low levels of physical fitness may also contribute to injuries in dancers.^{4,23}

Controlling Over-training or "Burnout"

The ever-increasing demand for better performances has forced preparation for dance to become virtually a year-round endeavour. However, very high quantities or intensities of physical stress may overload the physiological mechanisms of adaptation, and cause dancers to experience feelings of constant fatigue and lethargy, frequent respiratory tract infections, and reduced physical performance, among many other things. This condition has been called "burnout,"²⁴ "overtraining syndrome,"²⁵ or "unexplained underperformance syndrome."²⁶ Barron and Noakes²⁷ suggested that the overtraining syndrome is due to hypothalamic-pituitary dysfunction, as may be the case in very active females who frequently develop menstrual irregularities. However, menstrual irregularities may be secondary to reduced body-fat stores in these females, and therefore to lower energy reserves.^{28,29} Also, it has recently been suggested that overtraining induces a marked response of oxidative stress biomarkers, which may serve as a tool for overtraining diagnosis.³⁰

The condition tends to develop in dancers, regardless of their professional status, during periods of increased commitment to class or performance, with proportionally less time for recovery. In fact, it has been suggested that optimal recovery should be an integral part of any program designed to improve fitness and physical performance.³¹⁻³³ Data obtained through the use of biomechanical techniques—particularly dynamometry—indicate that 3 to 5 weeks of rest after the end of a professional season can lead to increases in most dance-related performance parameters, such as leg strength.³⁴

In individuals suffering from overtraining, loss of maximal voluntary muscle strength is among the confirming signs. However, the development of large muscle forces (i.e., strength and power) is a complex mechanism that depends on multiple steps leading from the central nervous system (i.e., the motor cortex in the brain), via the nerves, to the actual activation of muscle. Nevertheless, muscle strength may be affected even though muscle function is not impaired, as evidenced by a normal ability to respond to external electrical stimulation. This has led to the development of the "central-fatigue" hypothesis to explain reduced outputs during voluntary muscular exercise in overtrained individuals. This hypothesis is also in accord with reported data that show an impairment of the brain's central motor-drive in chronic fatigue syndrome sufferers.³⁵

Koutedakis and colleagues³⁶ tested this hypothesis by examining whether over-trained elite athletes were able to recruit all of their motor units during a 12-second isometric maximal voluntary contraction. During the last six seconds of the contraction an electrical impulse was superimposed on the exercising muscle by a computerized muscle stimulator. Figure 4 provides an example of the main findings. Electrical stimulation superimposed upon a healthy control subject failed to affect the performance of the quadriceps during isometric maximal contractions. This subject seems, therefore, to

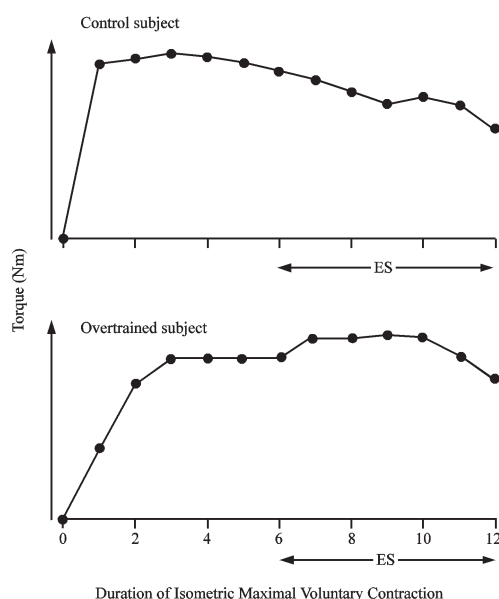


Figure 4 The effect of electrical stimulation (ES) superimposed on an isometric maximal voluntary contraction of the quadriceps muscle from (top) a healthy control and (bottom) an over-trained subject (Reproduced from: Koutedakis Y, Frischknecht R, Vrbova G, et al. Maximal voluntary quadriceps strength patterns in Olympic overtrained athletes. *Med Sci Sports Exerc.* 1995;27(4):566-72. With Permission.)

be able voluntarily to fully activate his muscles. In the over-trained subject, on the other hand, the added electrical stimulation increased the quadriceps torque, revealing an inability to voluntarily activate all of his muscle fibers. These data support the hypothesis of an impaired central drive in the brain as an explanation for muscular weakness in over-trained individuals.

Monitoring of Physical Fitness Flexibility

Dance is communication through human movement; therefore, optimum levels of flexibility, or range of motion (ROM), are essential for maximizing the versatility of movement. Dance educators have numerous methods of assessing improvements in flexibility, as a single comprehensive and reproducible methodology is difficult to achieve given the complex nature of human movement. Nevertheless, carefully controlled measurements, albeit in limited ranges of movement, can be made through the use of goniometers.

Goniometry is normally used to obtain information on joint positioning or ROM.³⁷ Simple goniometers measure static positions of limb seg-

ments with respect to a joint axis, whereas electrogoniometers involve a potentiometer (variable resistor) at the axis of rotation. An electrogoniometer provides a voltage output, proportional to joint angle, that can be measured, scaled, and recorded. This information can then be used to assess flexibility for diagnosis, rehabilitation, and exercise prescription.³⁸

Simple, mechanical, or electronic goniometry is the most frequently used biomechanical method for assessing ROM in both male³⁹ and female⁴⁰ dancers. On the other hand, it seems that strict audition policies in place in most reputable dance institutions ensure that young candidates already have the required ROM and, therefore, flexibility levels at the point of entry into the program. Such strict regimens have succeeded in transforming dance into an activity practiced by very flexible individuals, who have selectively developed different characteristics compared to ordinary individuals and athletes alike. "Flexible" dancers are able to withstand a stress level considerably in excess of what can be resisted by less flexible persons. Whether flexibility training also affects muscular strength

levels, and visa versa, remains to be confirmed in dancers.

Muscular Strength

The single most important contribution of biomechanics in relation to human physical performance is through its ability to monitor muscular strength. Strength is the ability to overcome external resistance, or to counter external forces, by using muscle. This is the result of the unique characteristic of the muscle cell, whereby it can convert the chemical energy of ATP into mechanical work.

Biomechanical dynamometry has frequently been used to obtain data regarding the tension developed by various muscle groups in dancers.⁴¹ Thus we know that dancers generally show lower strength levels than athletes,⁴² and within the dance world contemporary male and female dancers are stronger than their counterparts in ballet. Ballerinas appear to have the least muscular strength, demonstrating only 77% of the weight-predicted normal strength.⁴³ Low levels of muscular strength have been linked to increased injury rates found in dancers compared to other athletic populations.⁴

Dance-related adaptive changes, such as hip muscle strength in young female novice ballet dancers⁴⁴ and comparative hip external rotation strength and ROM between female dancers,¹⁹ can be observed with the help of selected biomechanical tools. These same tools can be used to reveal information regarding possible muscle imbalances, which can be extremely useful for both dancers and their teachers. Some additional examples of recent research findings through biomechanics that are relevant to muscle strength in dancers are as follows: 1. Contrary to the common belief that one side of the body is stronger than the other, strength studies in male and female dancers revealed no differences between left and right legs.^{18,34} 2. At muscle level, there are no obvious functional differences associated with force production in individuals participating in different

physical activities such as dance and rowing.⁴⁵ 3. Supplementary strength training contributes to strength improvements in male⁴⁶ and female dancers⁴⁷; such changes may occur without interfering with the dancers' artistic qualities⁴⁸; and, significantly, with concomitant increases in dance abilities.⁴⁹

Muscle Damage

High intensity eccentric exercise, without proper preparation, is associated with selected muscle damage parameters, including decreased ROM,⁵⁰ increased swelling,⁵¹ and delayed onset of muscle soreness.⁵² It also causes decrements in muscle performance, as evidenced by the reduction in eccentric peak torque and peak isometric force assessed by biomechanical techniques (e.g., isokinetic dynamometry).⁵³ Muscle damage and muscle performance are further affected by medium intensity eccentric exercise.^{54,55} Unfortunately, no data are available on the effects of different intensities of eccentric exercise on dancers' leg muscle damage and performance. Such knowledge could help dance educators and choreographers to create effective movement patterns that not only advance dance aesthetics but, most significantly, minimize the risk of developing dance-related injuries. It might be worth noting here that what is aesthetically pleasing is not necessarily acceptable and safe from a physiologically or biomechanically point of view.

Scheduling Training and Exercise Sessions

Biomechanics may also assist dancers and their teachers in developing effective scheduling (or periodization) plans. Systematic scheduling has increasingly become part of serious athletic training programs over the past half century. It sets out the format and the timescale of a complete training and competition plan. A similar approach may also be adopted by dancers, given that their lives tend to consist of constant cycles of hard work in class and rehearsal, followed by per-

formance, followed by layoffs of both short and relatively long duration.

Schedules are organized around the training unit (or training session), which aims at implementing the four basic principles of exercise training, namely specificity, reversibility, overload, and individuality. Training sessions should never be less than 30 minutes in length, which includes a 10-minute warm-up and cool-down increment (for more information see Koutedakis and Sharp¹).

A single formula for successful training to satisfy the needs of all individuals of varying ages, genders, and fitness levels does not exist. However, exercise scientists agree that a well conceived program should incorporate at least four distinct components: 1. optimum exercise intensity (i.e., load); 2. appropriate volumes of training; 3. specific rest periods between exercises; and 4. adequate recovery time between sessions.

Exercise Intensity

Exercise intensity may be defined as the exertion level that can cause positive physical and physiological adaptations. For instance, when an adult muscle is forced to contract at intensities that exceed 60% of its maximal force-generating capacity, adaptations occur that result in increases in strength. This normally accompanies better muscle fiber synchronization.

Volume of Exercise

The volume of training for a given exercise, or session, may be defined as the product of the number of sets, the number of repetitions, and the load in each repetition (sets X reps X load). In sport the relative magnitudes of these three volume components are critical. However, such a degree of specificity is not necessary in dancers. For them, maintenance of an individually tailored volume of physical exercise, in addition to their dance commitments, seems more appropriate. It should be stressed here that each individual has a different capacity for training with various volumes. Some may make substantial progress with longer or

more frequent periods of high-volume training sessions, while others may not. Dancers, therefore, should be careful when adopting the training cycles of other dancers or, particularly, sport competitors.

Rest Periods between Exercises

In dance, both experimental and anecdotal evidence supports the use of longer (greater than three minutes) rather than shorter rest intervals, in order to enhance the effects of subsequent bouts of muscular work. During these rest periods muscles recover most of the ability to work effectively by replacing the energy used during the preceding exercise bout and by removing the fatigue causing metabolic by-products. However, it has also been argued that the development of fatigue, through reduction of rest intervals, may accelerate the progress of selected fitness components.⁵⁶

Recovery from Training and Exercise

Two workouts per week per muscle group are sufficient to induce an optimum adaptive response; more frequent sessions may "overtrain" muscle. This thesis is supported by Ackland and Bloomfield,⁵⁷ who proposed a two-day recovery period between resistance-training sessions. More data are needed with specific reference to dance.

Conclusions

Biomechanics is the scientific discipline that studies the human body in motion. By applying principles from mechanics, engineering, and electronics, biomechanics is able to provide data on the forces that act upon the body and the effects they produce. Through the utilization of techniques such as motion capture, electromyography, dynamography, and dynamometry, biomechanics contributes to the advancement of knowledge in a variety of areas such as developmental biomechanics, biomechanics of exercise and sports (including dance), and rehabilitative biomechanics. In dance, biomechanical methodologies are used to improve

aspects of dance technique which, in turn, may help dancers and their teachers to prevent disabling injuries, to assess fitness levels and control overtraining (or “burnout”), and to plan effective scheduling of practice and exercise sessions.

References

- Koutedakis Y, Sharp NCC. *The Fit and Healthy Dancer*. Chichester: John Wiley and Sons, 1999.
- Mundermann L, Corazza S, Andriacchi TP. The evolution of methods for the capture of human movement leading to markerless motion capture for biomechanical applications. *J Neuroeng Rehabil*. 2006;3:6.
- Brown WM, Cronk L, Grochow K, et al. Dance reveals symmetry especially in young men. *Nature*. 2005;438(7071):1148-50.
- Shan G. Comparison of repetitive movements between ballet dancers and martial artists: risk assessment of muscle overuse injuries and prevention strategies. *Res Sports Med*. 2005;13(1):63-76.
- Trepman E, Gellman RE, Micheli LJ, De Luca CJ. Electromyographic analysis of grand-plié in ballet and modern dancers. *Med Sci Sports Exerc*. 1998;30(12):1708-20.
- Theoret D, Lamontagne M. Study on three-dimensional kinematics and electromyography of ACL deficient knee participants wearing a functional knee brace during running. *Knee Surg Sports Traumatol Arthrosc*. 2006;14(6):555-63.
- Nolan L, Kerrigan DC. Keep on your toes: gait initiation from toe-standing. *J Biomech*. 2003;36(3):393-401.
- Simmons RW. Sensory organization determinants of postural stability in trained ballet dancers. *Int J Neurosci*. 2005;115(1):87-97.
- Helin P. Activation in professional ballet dancers. *Physiol Behav*. 1988;43(6):783-7.
- Lepelley MC, Thullier F, Koral J, Lestienne FG. Muscle coordination in complex movements during jeté in skilled ballet dancers. *Exp Brain Res*. 2006;175(2):321-31.
- Moreside JM, Vera-Garcia FJ, McGill SM. Neuromuscular independence of abdominal wall muscles as demonstrated by middle-eastern style dancers. *J Electromyogr Kinesiol*. 2007, In press.
- Ravn S, Voigt M, Simonsen EB, et al. Choice of jumping strategy in two standard jumps, squat and countermovement jump-effect of training background or inherited preference? *Scand J Med Sci Sports*. 1999;9(4):201-8.
- Funato K, Yanagiya T, Fukunaga T. Ergometry for estimation of mechanical power output in sprinting in humans using a newly developed self-driven treadmill. *Eur J Appl Physiol*. 2001;84(3):169-73.
- Simpson KJ, Kanter L. Jump distance of dance landings influencing internal joint forces: I. Axial forces. *Med Sci Sports Exerc*. 1997;29(7):916-27.
- Harlaar J, Roebroeck ME, Lankhorst GJ. Computer-assisted hand-held dynamometer: low-cost instrument for muscle function assessment in rehabilitation medicine. *Med Biol Eng Comput*. 1996;34(5):329-35.
- Croisier JL, Foidart-Dessalle M, Tinant F, et al. An isokinetic eccentric programme for the management of chronic lateral epicondylar tendinopathy. *Br J Sports Med*. 2007;41(4):269-75.
- Dickin DC, Too D. Effects of movement velocity and maximal concentric and eccentric actions on the bilateral deficit. *Res Q Exerc Sport*. 2006;77(3):296-303.
- Westblad P, Tsai-Fellander L, Johansson C. Eccentric and concentric knee extensor muscle performance in professional ballet dancers. *Clin J Sport Med*. 1995;5(1):48-52.
- Gupta A, Fernihough B, Bailey G, et al. An evaluation of differences in hip external rotation strength and range of motion between female dancers and non-dancers. *Br J Sports Med*. 2004;38(6):778-83.
- Mattila KT, Komu M, Karsikas R, et al. Knee extension dynamometer: a new device for dynamic isokinetic magnetic resonance spectroscopy experiments. *Magma*. 1996;4(2):115-22.
- Schoene LM. Biomechanical evaluation of dancers and assessment of their risk of injury. *J Am Podiatr Med Assoc*. 2007;97(1):75-80.
- Koutedakis Y, Pacy PJ, Carson RJ, Dick F. Health and fitness in professional dancers. *Med Probl Perf Artists*. 1997;12(1):23-7.
- Koutedakis Y, Khalouha M, Pacy PJ, et al. Thigh peak torques and lower-body injuries in dancers. *J Dance Med Sci*. 1997;1(1):12-5.
- Koutedakis Y. “Burnout” in dance: the physiological viewpoint. *J Dance Med Sci*. 2000;4(4):122-7.
- Cosca DD, Navazio F. Common problems in endurance athletes. *Am Fam Physician*. 2007;76(2):237-44.
- Budgett R, Newsholme E, Lehmann M, et al. Redefining the overtraining syndrome as the unexplained underperformance syndrome. *Br J Sports Med*. 2000;34(1):67-8.
- Barron JL, Noakes TD, Levy W, et al. Hypothalamic dysfunction in overtrained athletes. *J Clin Endocrinol Metab*. 1985;60(4):803-6.
- Dueck CA, Manore MM, Matt KS. Role of energy balance in athletic menstrual dysfunction. *Int J Sport Nutr*. 1996;6(2):165-90.
- Dueck CA, Matt KS, Manore MM, Skinner JS. Treatment of athletic amenorrhea with a diet and training intervention program. *Int J Sport Nutr*. 1996;6(1):24-40.
- Margonis K, Fatouros IG, Jamurtas AZ, et al. Oxidative stress biomarkers responses to physical overtraining: implications for diagnosis. *Free Radic Biol Med*. 2007;43(6):901-10.
- Gleeson M, Pyne DB. Special feature for the Olympics: effects of exercise on the immune system: exercise effects on mucosal immunity. *Immunol Cell Biol*. 2000;78(5):536-44.
- Pyne DB, Gleeson M, McDonald WA, et al. Training strategies to maintain immunocompetence in athletes. *Int J Sports Med*. 2000;21(Suppl 1):S51-60.
- Tomlin DL, Wenger HA. The relationship between aerobic fitness and recovery from high intensity intermittent exercise. *Sports Med*. 2001;31(1):1-11.
- Koutedakis Y, Myszkewycz L, Soulas D, et al. The effects of rest and subsequent training on selected physiological parameters in professional female classical dancers. *Int J Sports Med*. 1999;20(6):379-83.
- Stokes MJ, Cooper RG, Edwards RH. Normal muscle strength and fatigability in patients with effort syndromes. *BMJ*. 1988;297(6655):1014-7.
- Koutedakis Y, Frischknecht R, Vrbova G, et al. Maximal voluntary quadriceps strength patterns in Olympic overtrained athletes. *Med Sci Sports Exerc*. 1995;27(4):566-72.

37. Alricsson M, Harms-Ringdahl K, Eriksson K, Werner S. The effect of dance training on joint mobility, muscle flexibility, speed and agility in young cross-country skiers—a prospective controlled intervention study. *Scand J Med Sci Sports*. 2003;13(4):237-43.
38. Kushner S, Saboe L, Reid D, et al. Relationship of turnout to hip abduction in professional ballet dancers. *Am J Sports Med*. 1990;18(3):286-91.
39. Askling C, Saartok T, Thorstensson A. Type of acute hamstring strain affects flexibility, strength, and time to return to pre-injury level. *Br J Sports Med*. 2006;40(1):40-4.
40. Steinberg N, Hershkovitz I, Peleg S, et al. Range of joint movement in female dancers and nondancers aged 8 to 16 years: anatomical and clinical implications. *Am J Sports Med*. 2006;34(5):814-23.
41. Bennell K, Khan KM, Matthews B, et al. Hip and ankle range of motion and hip muscle strength in young female ballet dancers and controls. *Br J Sports Med*. 1999;33(5):340-6.
42. Kirkendall DT, Calabrese LH. Physiological aspects of dance. *Clin Sports Med*. 1983;2(3):525-37.
43. Reid DC. Prevention of hip and knee injuries in ballet dancers. *Sports Med*. 1988;6(5):295-307.
44. Bennell KL, Khan KM, Matthews BL, Singleton C. Changes in hip and ankle range of motion and hip muscle strength in 8-11 year old novice female ballet dancers and controls: a 12 month follow up study. *Br J Sports Med*. 2001;35(1):54-9.
45. Koutedakis Y, Agrawal A, Sharp NCC. Isokinetic characteristics of knee flexors and extensors in male dancers, olympic oarsmen, olympic bobsleighers and non-athletes. *J Dance Med Sci*. 1998;2(2):63-7.
46. Koutedakis Y, Cross V, Sharp NCC. The effects of strength training in male ballet dancers. *Impulse*. 1996;4(3):210-9.
47. Koutedakis Y, Jamurtas A. The dancer as a performing athlete: physiological considerations. *Sports Med*. 2004;34(10):651-61.
48. Koutedakis Y, Sharp NC. Thigh-muscles strength training, dance exercise, dynamometry, and anthropometry in professional ballerinas. *J Strength Cond Res*. 2004;18(4):714-8.
49. Koutedakis Y, Hukam H, Metsios G, et al. The effects of three months of aerobic and strength training on selected performance- and fitness-related parameters in modern dance students. *J Strength Cond Res*. 2007;21(3):808-12.
50. Nosaka K, Sakamoto K, Newton M, Sacco P. How long does the protective effect on eccentric exercise-induced muscle damage last? *Med Sci Sports Exerc*. 2001;33(9):1490-5.
51. Soricter S, Mair J, Koller A, et al. Creatine kinase, myosin heavy chains and magnetic resonance imaging after eccentric exercise. *J Sports Sci*. 2001;19(9):687-91.
52. Jamurtas AZ, Fatouros IG, Buckenmeyer P, et al. Effects of plyometric exercise on muscle soreness and plasma creatine kinase levels and its comparison with eccentric and concentric exercise. *J Strength Cond Res*. 2000;14(1):68-74.
53. Paschalis V, Koutedakis Y, Jamurtas AZ, et al. Equal volumes of high and low intensity of eccentric exercise in relation to muscle damage and performance. *J Strength Cond Res*. 2005;19(1):184-8.
54. Golden CL, Dudley GA. Strength after bouts of eccentric or concentric actions. *Med Sci Sports Exerc*. 1992;24(8):926-33.
55. Nosaka K, Clarkson PM. Muscle damage following repeated bouts of high force eccentric exercise. *Med Sci Sports Exerc*. 1995;27(9):1263-9.
56. Schott J, McCully K, Rutherford OM. The role of metabolites in strength training. II. Short versus long isometric contractions. *Eur J Appl Physiol Occup Physiol*. 1995;71(4):337-41.
57. Ackland TR, Bloomfield J. Science and medicine in sport. In: Bloomfield J, Fricker PA, Fitch KD (eds): *Applied Anatomy*. Oxford, England: Blackwell, 1995, pp. 2-31.